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INFLUENCE OF NOZZLE CONTRACTION ON THE DAMPING OF TURBULENT PULSATIONS

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16. Abstract

The influence of large longitudinal pressure gradients generated by contracting nozzles on the equilization of the velocity and pressure fields, on the damping of turbulent velocity pulsations, and on the initial disturbances in the flow is studied experimentally. It is shown that with increasing degree of nozzle contraction, the degree of turbulence at the nozzle exit section decreases, however, the longitudinal and transverse components of the velocity pulsations increase regardless of contraction.

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INFLUENCE OF NOZZLE CONTRACTION ON THE DAMPING OF TURBULENT PULSATIONS

L. N. Voytovich

In the design of wind tunnels, the uniform flow with a low degree of turbulence in the working section must be taken into account. To decrease nonuniformity and flow turbulence in wind tunnels, honeycombs are used, as well as fine wire screens placed in the forechamber of the tunnel. Nozzles with a large contraction coefficient, providing a low velocity in a large portion of the tunnel, make it possible to use honeycombs and screens to quench the turbulence without great losses. / 112*

The influence of contraction on turbulent velocity pulsations was first studied by L. Prandtl [8], under the assumption that turbulent velocity pulsations in an incompressible liquid can only be caused by vorticity and must be found by the vorticity distribution. He assumes that the velocity pulsations in the direction of the average flow were caused by vortex tubes, whose axes are perpendicular to the longitudinal axis. Similarly, transverse velocity pulsations are caused by vortices, whose axes are perpendicular to the transverse nozzle cross section. When passing through the nozzle, the vortex tubes are extended in the ratio n in the direction of the average flow, and the vortex tubes in a direction which is perpendicular to the average flow are contracted in the ratio $\sqrt{n}$ where $n=u_2/u_1$ is the ratio of the average

* Numbers in the margin indicate pagination of original foreign text.

velocities in the working section and the forechamber. However, the intensity of the vortex tube (product of the angular velocity by the transverse cross section area) remains constant. Thus, the angular velocity of the vortex tubes directed along the tunnel axis increases in the ratio n and the nozzle radius decreases in the ratio $\sqrt{n}$. As a result, the circular velocity and the corresponding transverse pulsation velocity increase by a factor of $\sqrt{n}$.

On the other hand, the area of the transverse section of the vortex tube, which is perpendicular to the longitudinal axis, increases by a factor of $\sqrt{n}$ and its angular velocity correspondingly decreases. The distance to the center of the vortex tube also decreases in the ratio $\sqrt{n}$. As a result, the circular velocity and correspondingly the longitudinal pulsation velocity u' decrease by a factor of n^{-1}. The Prandtl theory is based on the behavior of the discrete vortex tubes.

G. Taylor [5], assuming a specific form for the initial perturbation and disregarding the damping, showed that in the case of isotropic initial turbulence the absolute value of the longitudinal pulsations decreases by a factor of seven, and not by a factor of n^{-1}, as Prandtl assumed, and also showed that the influence of the contraction greatly depends on the nature of the initial perturbation. Taylor obtained the same results as Prandtl for transverse pulsations. Thus, the results of studies by Taylor for different types of flows differ from the results of Prandtl only in the values of the numerical coefficients. /113

Ribner and Tucker [9] studied the influence of contraction on the spectral characteristics of turbulence, utilizing the concepts of Prandtl and Taylor. They, like Taylor, assuming weak turbulence, assumed that the distortions of the turbulent vortices are small as compared with the distortion caused by contraction of the main flow. This assumption made it possible to linearize the problem. In addition, the liquid was assumed to be inviscid, which excluded the consideration of turbulence damping. In the case of axisymmetric contraction and isotropic initial turbulence, the same dependence on contraction n of the transverse pulsations was obtained as that obtained by Prandtl, with the exception of the numerical coefficients.

There are many studies which describe experiments investigating the effect of contraction on damping of turbulent pulsations [2, 3, 4, 6]. However, the results of these experiments differ from each other considerably.

The first experiments to check the theory of Prandtl were performed by Fage in 1934 [4]. He found that longitudinal velocity pulsations v' under the action of contraction change insignificantly, whereas transverse velocity pulsations u' decrease in the ratio $n^{-\frac{1}{2}}$. These results were at variance with the Prandtl theory.

Macphail, measuring the longitudinal and transverse components of pulsation velocity on the nozzle axis with a contraction coefficient of $n \approx 10$, found that with in the case of contraction the isotropic nature of the turbulence is disturbed, and the longitudinal component of the pulsation velocity u' decreases while the transverse component v' increases greatly. However, at the end of the nozzle both components have a tendency to equalize.

Studies of the influence of contraction on the isotropic turbulence in the case of n = 4.9 and 16 were performed by Uberoi [10]. His measurements showed that in the case of flow acceleration in nozzles with contractions of 4 and 9 the longitudinal pulsation component decreases and the transverse component increases. With contraction of 16, the longitudinal component first decreases, and then increases up to a value which exceeds the initial value. At the end of the nozzle, the turbulent energy of the longitudinal and transverse velocity components slowly equalizes. Turbulence spectra were measured before and after contraction.

The present study was performed to accumulate experimental data on the influence of large negative longitudinal pressure gradients produced by nozzles having an identical contour and differing contraction upon the equalization of the velocity and pressure fields, and also upon the damping of the turbulent velocity pulsations and the initial flow perturbations. A wider range of contractions was studied than in other investigations (from 4 to 25).

EXPERIMENTAL EQUIPMENT. EXPERIMENTAL METHOD

The experiments were performed on the equipment shown in Figure 1. Nozzles having a circular transverse cross section and differing contraction (n was approximately equal to 4, 8, 12, 16 and 25) were placed behind the forechamber which represented a circular tube with a diameter of 425 mm and a length of 950 mm. Two screens were initially placed at the forechamber inlet, made of wire with a diameter of 0.4 mm and a mesh dimension of M = 65 mm. The distance from the second screen up to the input section of the nozzle was (x/M=394). Honeycombs were placed /114 before the second screen with square mesh of 10 x 10 mm and a mesh depth in the direction of the flow of 60 mm. The screen was thus displaced by 150 mm toward the input section of the nozzle (x/M=303).

During the experiment, the air was forced through the forechamber by a centrifugal fan and was drawn out from the nozzle into free space. The air flow rate was regulated by a throttle device with a moveable diaphragm, making it possible to change the

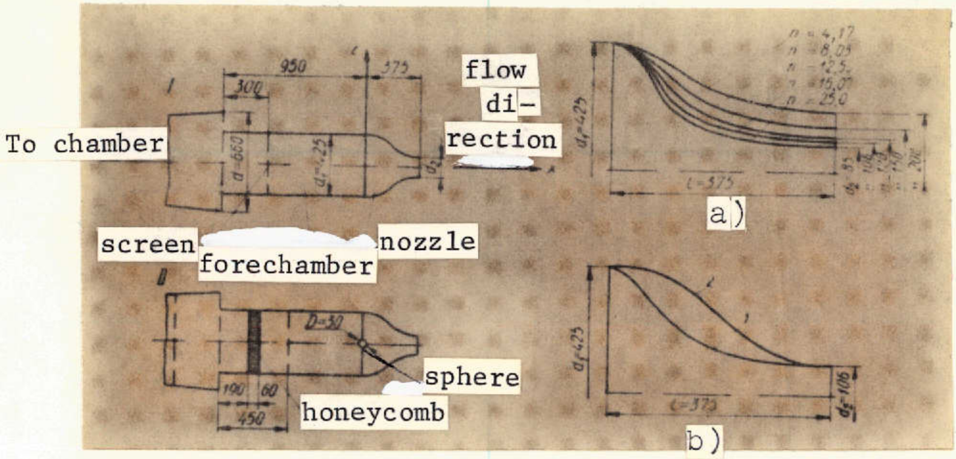

Figure 1

flow rate smoothly. Interchangeable nozzles had an identical length 150 mm, and their contours followed a curve determined by the formula of Ye. Vitoshinskiy (see Figure 1 a).

Measurements of the longitudinal u' and transverse v' and w' components of the pulsation velocity were performed by a thermoanemometric device of the "Disa Elektronik" firms. For the measurements, use was made of unifilar and cruciform nozzles, whose filaments were made of a platinum Wollaston wire with a diameter of 8μ. The velocity and pressure of the flow were measured by a Pitot-Prandtl tube.

The adapters were fastened by means of a rod in a coordinate system, making it possible for them to be displaced in directions either longitudinal or transversed to the flow. The tests were performed at the constant flow velocity in the input section of the nozzle which equals 2 m/sec. The velocity at the output of the nozzle increased in accordance with the nozzle contraction. The regime was controlled by the static pressure drop in the forechamber and at the output from the interchangeable nozzles.

TEST RESULTS

Field of velocities and pressures at the output section of the nozzle. Figures 2 and 3 show the distribution of the dynamic $(\mu = q/q_2)$ and static $[\bar{p} = (p - p_{\text{атм}})/q_2]$ pressures along the radius $(\bar{r} = r/r_2)$ of the output section of the nozzle. Here q_2 is the dynamic pressure in the center of the output nozzle section. The measurements were performed on the device without a honeycomb 1 and with a honeycomb 2.

A comparison of the diagrams shows that an increase in the degree of contraction improves the quality of the flow in the output nozzle cross section. Thus, on equipment with a honeycomb with an increase in n from 8 to 25 the maximum nonuniformity of the static pressure $\bar{p}$ decreases from 2.9% to 1.4%, and of the dynamic pressure μ from 2.7% to 1.2%. Installation of the honeycomb in the forechamber produced a small increase in non-uniformities in the output nozzle cross section. / 115

Pulsation velocity components. Figure 4 shows the change in the degree of turbulence along the nozzle axis, which was determined from the longitudinal and transverse components of the pulsation velocity: $\varepsilon_u = \sqrt{\overline{u'^2}}/u$ and $\varepsilon_v = \sqrt{\overline{v'^2}}/u$, where $\sqrt{\overline{u'^2}}$ and $\sqrt{\overline{v'^2}}$ are the mean square values of longitudinal and transverse pulsations; u — average local velocity of the flow. Measurements which were initially carried out showed that the transverse pulsation components — the radial v' and the tangential w' — barely differ, and therefore only one of them is shown on the graphs, namely v'.

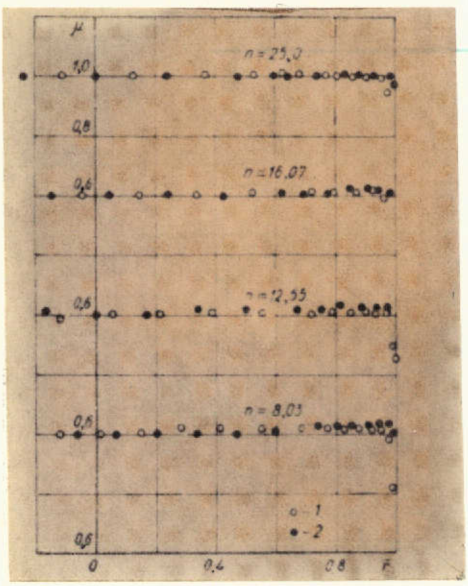

Figure 2

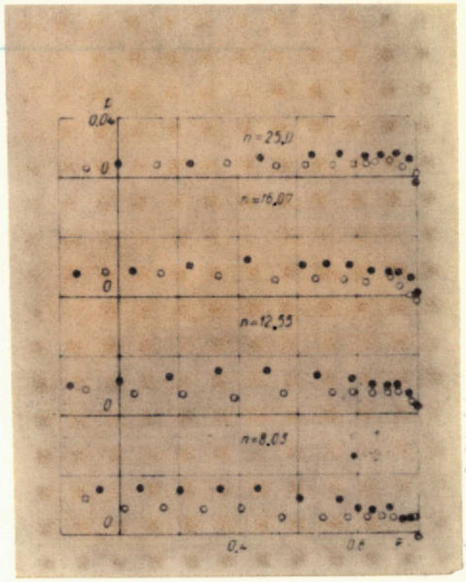

Figure 3

The degree of turbulence over the nozzle length decreases, and depends on the contraction coefficient at the output of the nozzle. When n changes from 4.17 to 25 ε_u decreases by approximately a factor of two, and ε_u — by a factor of 2.5. Thus, the difference in the degree of turbulence at the input to interchangeable nozzles may be explained by the fact that, when the flow regime was controlled, consideration was not given to the decreased areas of the output nozzle cross section, caused by the introduction of the rod with the adapter attached to it.

When a honeycomb was placed in the forechamber (Figure 5), the level of turbulence at the input to the nozzle was decreased by approximately a factor of 1.5. However, in the nozzle the low turbulence levels were damped to a lesser extent, as a result of which the value of ε_u in the nozzle output section remains practically the same as in the installation without the honeycomb.

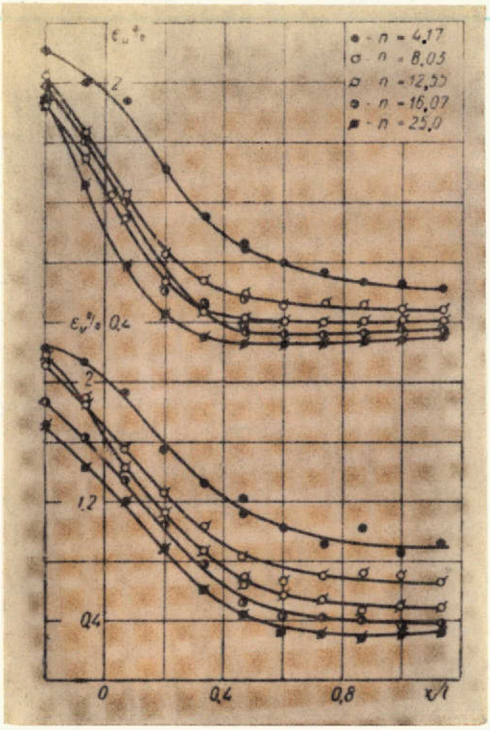

Figure 4

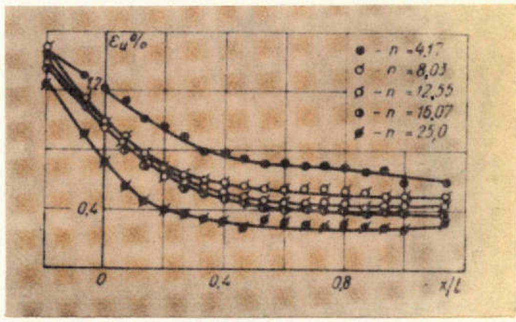

Figure 5

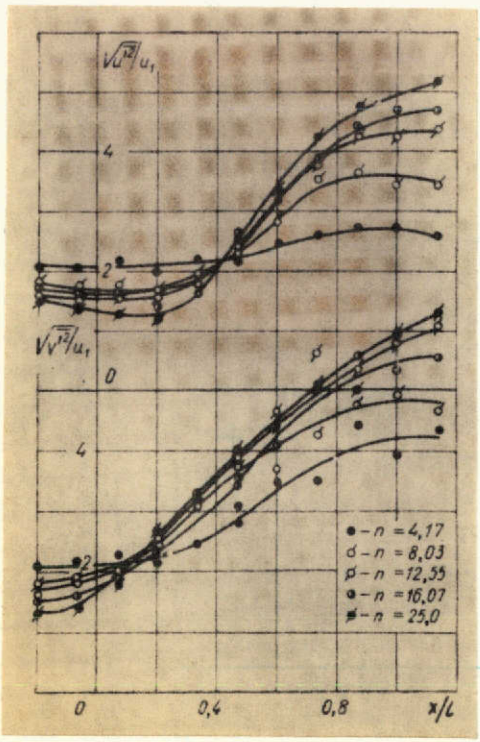

Figure 6

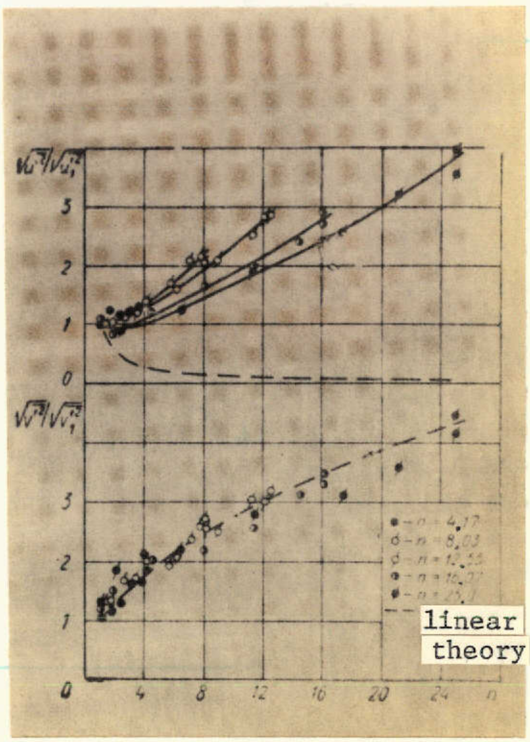

Figure 7

The longitudinal and transverse components of the velocity pulsation (Figure 6) increase along the flow in the nozzles. A comparison of the experimental results (Figure 7) with the calculations obtained from linear theory [9] shows that there is great divergence of the data with respect to the longitudinal pulsations. Based on linear theory, the longitudinal pulsation component must decrease in the case of contraction and its decrease — just like the increase in the transverse component — obeys one and the same law for all contractions. The experimental results revealed the differing nature of the increase in the longitudinal pulsation component with an identical velocity increase in the nozzles with differing contraction. Apparently, the assumption regarding a flow contraction which is so rapid that the forces of viscosity and inertia do not have a substantial influence on the turbulent motion leads to this divergence between theory and experiment. Theory also disregards the differing para- /117 meters of the initial turbulence.

Influence of Reynolds number. Figure 8 shows the change in the degree of turbulence ε_u and ε_v for a nozzle with the contraction $n \approx 16$, tested at different Re_M = 110, 220 and 330 numbers. The Re_M number was determined from the average velocity at the nozzle input, which was variable in these experiments, and from the dimensions of the screen mesh. As may be seen from the graph, an increase in the Re_M number has a differing influence upon the degree of turbulence determined from the longitudinal and transverse pulsation components: at the output from the nozzle ε_u decreases, and ε_v increases with an increase in Re_M.

Influence of nozzle contour. It is known that the form and length of the curve forming the nozzle contour has a great influence on the flow uniformity in the output section. With a small contraction coefficient $n \approx 5$ and a nozzle length of $l \approx 2\ d_2$, the requirement for uniformity of the nozzle form, determined by the

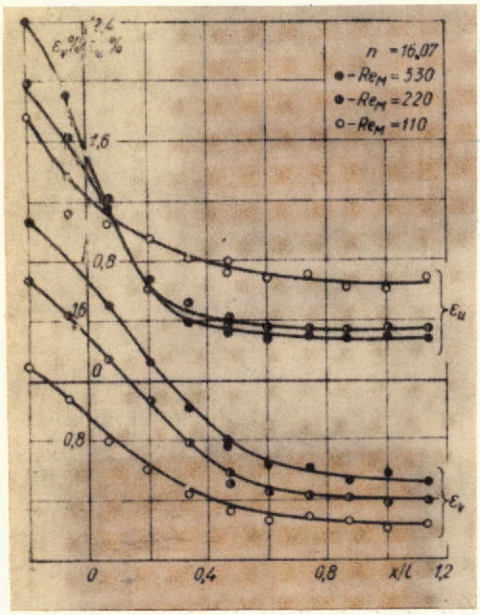

Figure 8

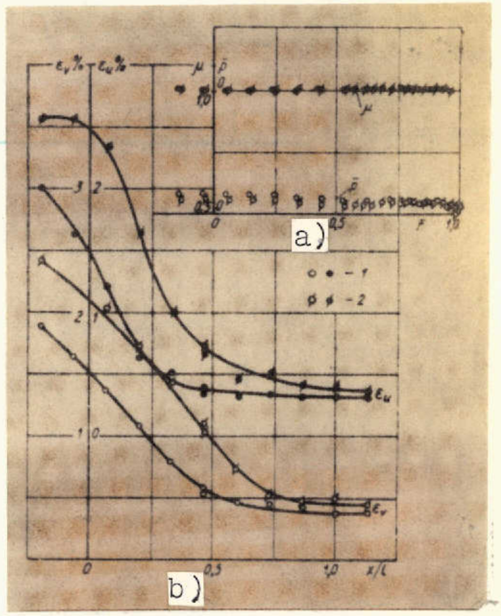

Figure 9

Vitoshinskiy formula [1] is satisfied. However, a nozzle with this contour has a long section of high velocity and correspondingly high hydraulic losses. A study was made of the influence of the nozzle contour change upon the uniformity and turbulence of flow with a large contraction coefficient $n \approx 16$ and a length of $l \approx 3.5\ d_2$. For this purpose, the nozzle 2 was tested (see Figure 1, b). The law governing the change in the passages of this nozzle differed greatly from the law corresponding to the formula of Vitoshinskiy (nozzle 1). This type of nozzle contour was studied previously in [10].

Figure 9, a shows that a nozzle with a contour which is more loaded 2 has a uniform distribution of dynamic and static pressure in the output section, which practically coincides with corresponding distributions for the nozzle 1 built following the Vitoshinskiy curve. A comparison of the degree of turbulence on the nozzle axis (Figure 9, b) also reveals insignificant differences between these values at the output section of the nozzle.

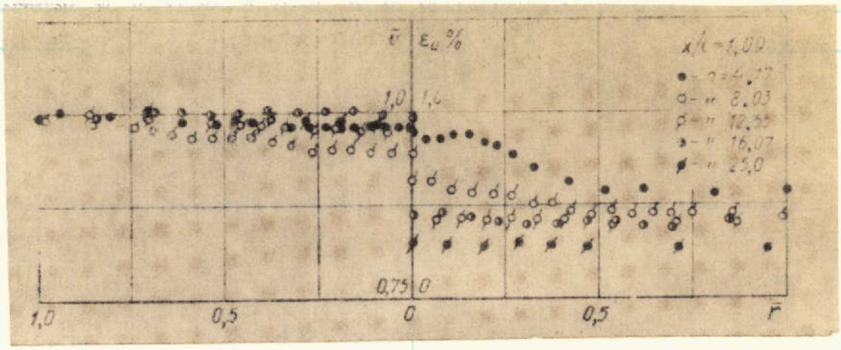

Figure 10

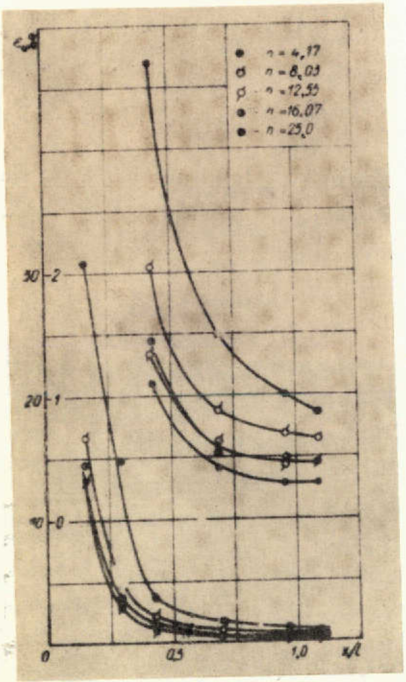

Figure 11

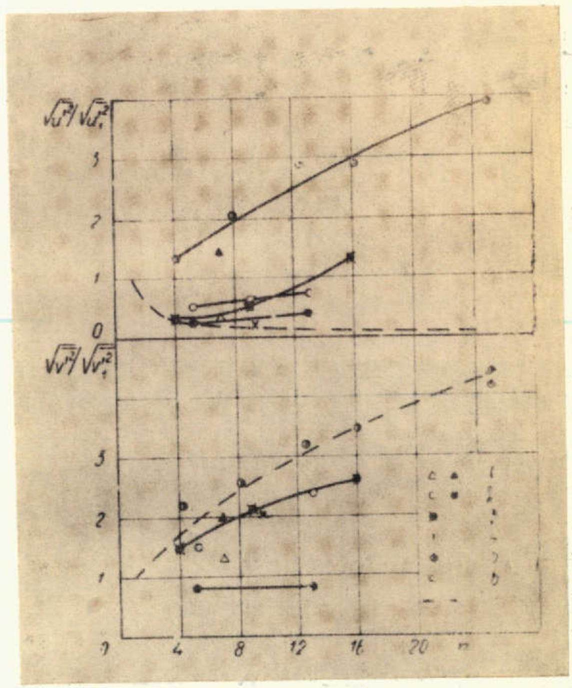

Figure 12

In addition, the nozzle with a more loaded contour has smaller hydraulic losses.

<u>Damping of axisymmetric perturbation.</u> In order to make a qualitative determination of the damping characteristics of the initial perturbations in nozzles with differing contraction coefficients, a study was made of the damping of the turbulent /118

wake behind a sphere with the diameter D = 30 mm, which was originally attached on the axis of the input nozzle section (see Figure 1). The Re_p number, determined from the incoming flow velocity and the sphere diameter, equals 4600. The change in the average velocity $\bar{u}=u/u_b$ (u_b — velocity at the wake boundary) and the longitudinal component of the pulsation velocity ε_u in the output section and along the nozzle axis (Figures 10 and 11) shows that for $Re_D=4.6\cdot10^3$ in the case of large negative pressure gradients $(n\geqslant12)$ the axisymmetric wake completely damps at a distance $x/l\approx1$ from the perturbation source. In this section, the degree of turbulence has the same value as when there is no perturbation (see Figure 5). For contraction coefficients which are less than 12, the pulsation wake is retained up to the output nozzle section.

The upper part of Figure 11 gives the values of ε_u, corresponding to $x/l>0{,}4$ in a large scale. /119

In conclusion, Figure 12 gives a comparison of the results of the experiments by different authors on the influence of contraction upon turbulent velocity pulsations (1—experiments of [3] (without screens and behind six screens); 2—experiments of [6] (without a honeycomb and with a honeycomb); 3—experiments of [10]; 4—experiments of [7]; 5—experiments by the author; 6—calculations given in [2]). The results from calculations according to linear theory [9] are given.

Deviations of the experimental data from the results calculated according to linear theory may apparently be explained not only by assumptions included in the theory (rapidity of contraction, disregard of damping), but also by the unusual initial experiment conditions in the input nozzle section. The form of the perturbations, the initial intensity and scale of turbulence in the input nozzle section have a great influence on the damping of the turbulent pulsations in the case of contraction.

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